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EXERGY ANALYSIS OF OFFSHORE PROCESSES ON NORTH SEA OIL AND GAS PLATFORMS

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Abstract

Offshore processes are associated with significant energy consumption and large CO_2 emissions. Conventional North Sea oil and gas facilities include the following operations: crude oil separation, gas compression and purification, wastewater treatment, gas lifting, seawater injection and power generation. In this paper, the most thermodynamically inefficient processes are identified by performing an exergy analysis, based on models built with the simulation tools Aspen Plus®, DNA and Aspen HYSYS®. Results reveal that the total exergy destruction of the system amounts to 69.4 MW, while the total exergy losses amount to 22.3 MW. The gas lifting train and the production-separation module are the most exergy-destructive operations of the oil and gas processing system, consuming 8.83 MW and 8.17 MW respectively, while the power generation system alone is responsible for 46.7 MW. The exergetic efficiency of the oil and gas processing is about 39%, while the exergetic efficiency of the utility system is about 21-27%.

1 Introduction

North Sea oil and gas platforms were responsible for about 4% of the total gross primary energy consumption and CO_2 emissions of Denmark in 2011. It is generally assumed that the energy intensity and environmental impact of these offshore facilities will increase in the coming years, as a direct consequence of larger energy use to enhance hydrocarbon production [1]. Oil and gas platforms are usually designed for the early life of a petroleum field. Therefore, since production flows and operating conditions tend to change significantly over the life cycle of the facility, the various processes taking place on the platform may be strongly affected as time goes on.

Concerns exist about the possible ways of evaluating and increasing the performance of these operations. Exergy analysis is a method based on the 2nd law of thermodynamics which has been widely used to characterise the efficiency of various industrial processes. Exergy is defined as the maximum theoretical useful work that can be extracted from any given system, in reference to a specific environment. Unlike energy, exergy can be destroyed; this enables locating and quantifying sources of thermodynamic irreversibilities [2, 3]. Exergy analyses of offshore platforms have been conducted by Oliveira et Van Hombeeck [4], as well as by Voldsund et al. [5, 6].

Oliveira et Van Hombeeck simulated a Brazilian petroleum plant with HYSYM and focused exclusively on the separation, compression and pumping modules. Results showed that the most exergy-consuming steps were the petroleum heating, which was part of the separation module, and the gas compression. The separation step had the worst exergetic efficiency (22.2%) of the overall plant, which had an exergetic efficiency of 9.7%. The authors suggested that the large exergy destruction taking place in the heating step was due to the high difference between the temperatures of the exhaust gases and of the petroleum, and that newer separation technologies could present exergy benefits.

Voldsund et al. simulated a specific North Sea offshore platform by using Aspen HYSYS®. The platform investigated in their study included separation, recompression and reinjection trains as well as fuel gas and export pumping systems. Results showed that the largest exergy destructions occurred in the gas re-injection trains (44.4%) and in the recompression ones (17%). The authors reported an overall exergetic efficiency of 32% in the baseline case and suggested that the thermodynamic losses of the platform could be greatly reduced by avoiding anti-surge recycling and using more efficient compressors [6].

The goal of this paper is to assess the thermodynamic performance of the different processes taking place on a typical North Sea oil and gas platform based on an exergy analysis. This study aims to complement the previous works of Oliveira [4] and Voldsund [6] by including additional processes of relevance such as the gas flaring and lifting systems, the wastewater treatment process and the water injection system [7], which were not investigated in the researches previously led within this field. Computations were conducted using the software Aspen Plus®, DNA and Aspen HYSYS®.

2 Methodology

Typical processes on a North Sea oil and gas platform are shown in Figure 1: production manifold, petroleum separation, gas re-compression and purification, oil export pumping, gas flaring and lifting, wastewater treatment, water injection and power generation.

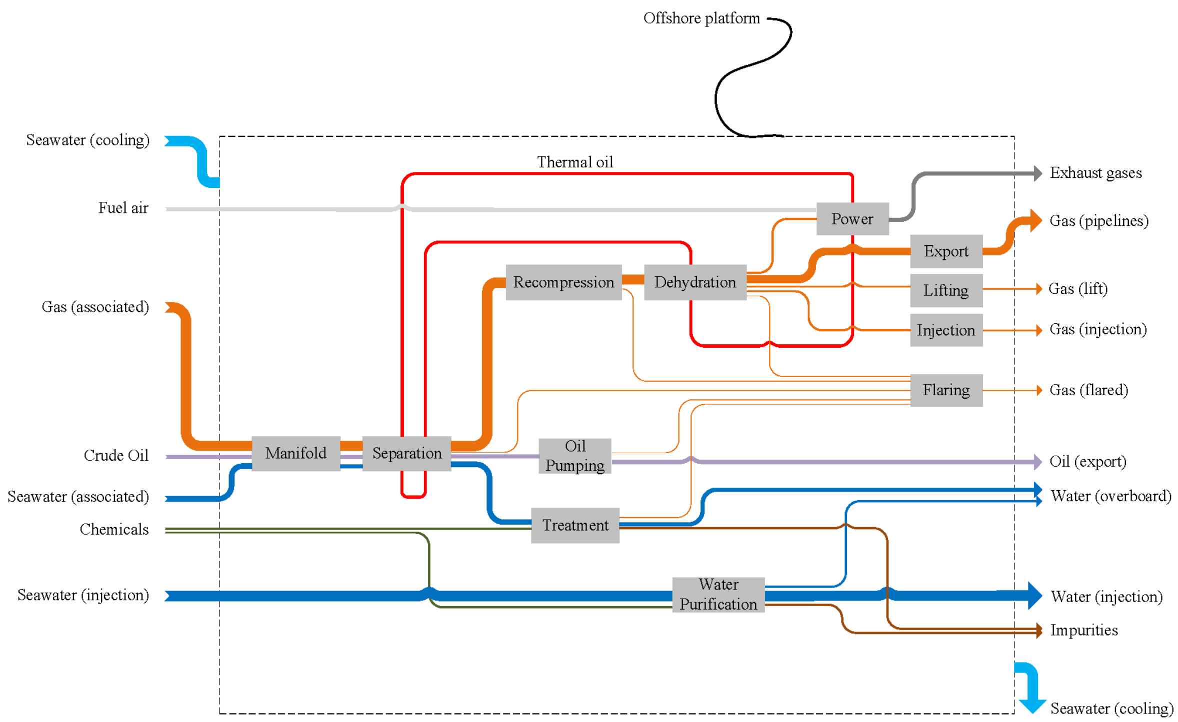

Figure 1: Conceptual layout of offshore processes on a North Sea oil and gas platform

2.1 System definition

The main function of the facility is to separate oil, gas and water. Petroleum by itself is relatively dry and has a low content of light hydrocarbons, but is extracted along with water and gas on typical platforms. Oil is shipped onshore, while gas may either be exported to the coast or injected into the reservoir to enhance the crude oil production. Water is treated on-board and re-injected into the reservoir [7, 8]. The processes introduced in Figure 1 are included in this study and a simplified overview of this system, delimiting its inputs, outputs and boundaries, is presented in Figure 2.

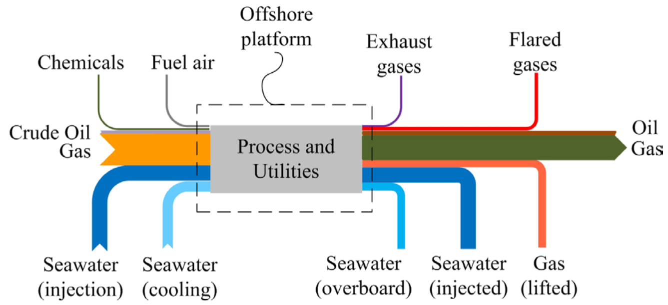

Figure 2: Conceptual representation of an offshore oil and gas platform

2.2 Exergetic analysis

Unlike energy, exergy derives from the 2nd law of thermodynamics and is not conserved in real processes [2]. Exergy balance for a control volume at steady state with negligible potential and kinetic effects is expressed as:

$$\sum_e \dot{m}_e e_e - \sum_i \dot{m}_i e_i + \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W}_{cv} = \dot{E}_d \tag{1}$$

Where e is the specific exergy of a material stream, T_0 and T_j the temperatures associated with the environment and the heat transfer process. The specific exergy of a stream of matter e is a function of its physical e_{ph}, chemical e_{ch}, kinetic e_{kn} and potential e_{pt} compounds, written as follows:

$$e = e_{ph} + e_{ch} + e_{kn} + e_{pt} \tag{2}$$

Physical exergy is related to temperature and pressure differences with the environment, while chemical exergy is related to differences in chemical composition and is calculated from Szargut´s model [9]. It is assumed in this study that kinetic and potential exergy contributions are negligible. Applying an exergy balance on a specific process component k and calculating its exergy destruction rate $\dot{E}_{d,k}$, provides information on its inefficiencies. The exergy destruction rate of this component can then be related to the exergy destruction rate of the whole system $\dot{E}_d$ by calculating the exergy destruction ratio y_k^*, defined as:

$$y_k^* = \frac{\dot{E}_{d,k}}{\dot{E}_d} \tag{3}$$

2.3 Exergetic efficiency

Exergetic efficiency η_k for a sub-system k, which is a measure of its thermodynamic performance, can be defined by identifying fuel and product of interest. It should be emphasised that fuel and product exergies $\dot{E}_{f,k}$ and $\dot{E}_{p,k}$ of the sub-system of interest are not necessarily equal to its input and output exergies. Definitions of fuel and product exergies are given in Bejan et al. [2].

$$\eta_k = \frac{\dot{E}_{p,k}}{\dot{E}_{f,k}} \tag{4}$$

3 Modelling and simulation

3.1 Plant description and modelling

Petroleum is extracted at several wells and transferred to the platform complex via a network of pipelines and a system of production manifolds. The individual well streams are mixed and depressurised by choke boxes to around 7 MPa, and fed afterwards into the separation train. As shown in Figure 2, crude oil separation is promoted by gravity and takes place in four stages operating at four different pressure levels (7, 2.92, 0.79 and 0.18 MPa). The first three stages consist of three- and two-phase separators while the last stage comprises an electrostatic coalescer. Pressure is decreased along the train by a series of throttling valves and the temperature of the separator feeds is increased by heat exchange with thermal oil to 40-45°C to increase the separation efficiency.

Product gas from the separators is led through the re-compression train. Temperature is decreased to 30-35°C by seawater cooling and liquid droplets are removed by scrubbing, resulting in a relatively dry gas which is then pressurised to 7 MPa.

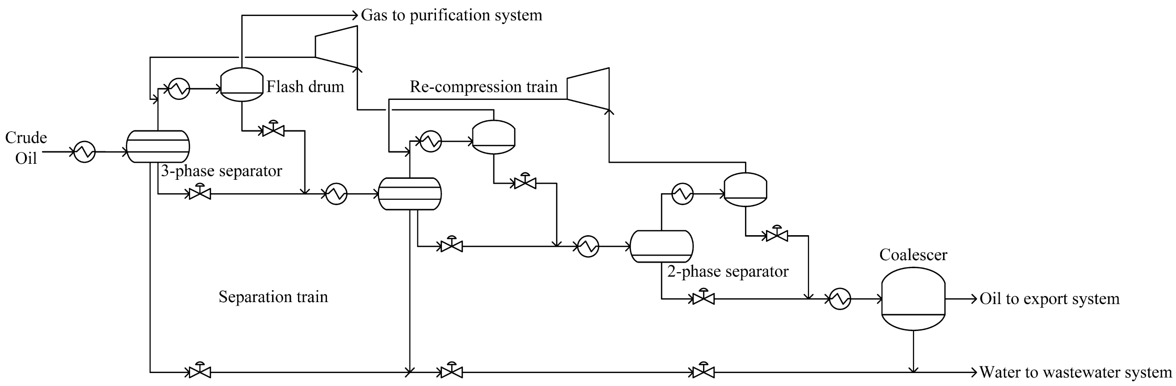

Figure 3: Flow sheet of the separation and gas re-compression trains

Raw natural gas from the re-compression train must be purified to be further utilised. In general, gas processed from the North Sea has a relatively low content of hydrogen sulphide but carries other impurities such as heavy hydrocarbons and water vapour. For corrosion and quality issues, there is a need for a dehydration unit, as illustrated in Figure 4. Wet gas enters at 7 MPa at the bottom of an absorption column and water is removed by physical absorption with liquid glycol, at a ratio of 35 litres per kg of water. Glycol is then regenerated in a distillation column operating between 98.9°C and 204.4°C at a lower pressure and separated from water vapour which is released to the atmosphere.

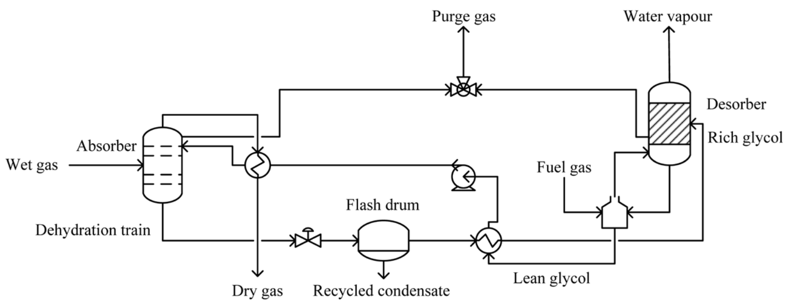

Figure 4: Flow sheet of the glycol dehydration unit

Dry gas is then split into three main flows. A small fraction is sent to three power generation units, two twin-spool gas turbine systems, as presented in Figure 5, and one one-spool. Fuel gas is mixed and burnt with compressed air in a combustion chamber. Flue gases from the combustion chambers of the two two-spool gas turbine systems are expanded, fed to a waste heat recovery system to heat up thermal oil, and rejected to the environment. Conversely, flue gases from the combustion chamber of the one one-spool gas turbine system are discharged to the surroundings after expansion.

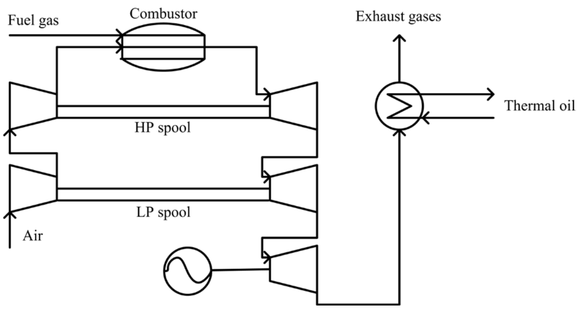

Figure 5: Flow sheet of the main power generation unit

The second fraction of the dry gas is used for lifting—injecting high-pressure gas into the reservoir to increase petroleum recovery. Lifting gas is cooled and scrubbed to further remove heavy hydrocarbons and to decrease the power requirements of the compressors. This process is similar to the re-compression process. The last fraction of the dry gas is sent onshore through a network of subsea pipelines at 18 MPa. Oil from the separation train enters the export pumping system, where it is mixed with oil removed in other steps of the plant, cooled, pumped and exported.

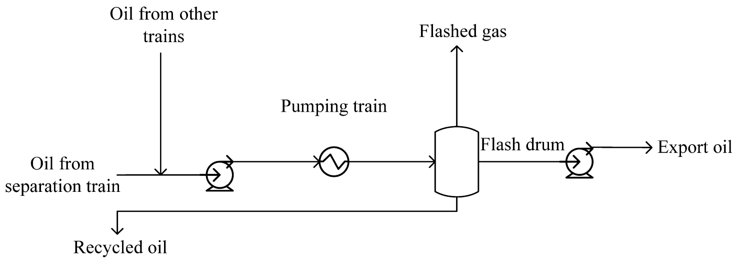

Figure 6: Flow sheet of the export pumping train

Water removed from the plant must meet several quality requirements before being discharged overboard or re-injected into the reservoir. Water flows through a flash vessel where hydrocarbon and oxygen traces are removed, is mixed with chemical coagulants and is fed into a hydro-cyclone where it is cleaned of sediments. In parallel, seawater is processed in filtering, deaeration and biological treatment units before being pumped and injected into the petroleum reservoir.

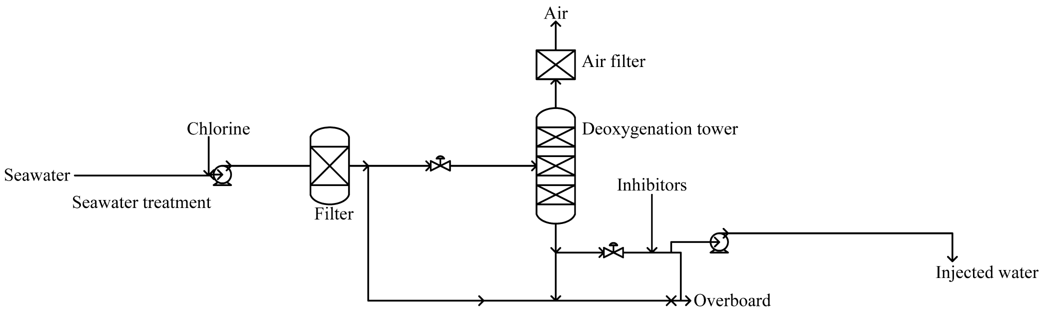

Figure 7: Flow sheet of the seawater injection system

3.2 Simulation basis

Conventional chemical analyses cannot determine the exact composition of crude oil because of its complex composition. Petroleum is thus modelled as a group of known and hypothetical components to estimate thermo-physical and chemical properties. In this work, sweet crude oil with an API gravity of 39.9, a specific gravity of 0.826, a density of 823.5 kg.m^{-3} and a light ends cut of 27.2% in volume was considered. Production manifolds, petroleum separation, gas re-compression, flaring and lifting, oil pumping, water treatment and re-injection are simulated with Aspen Plus® version 7.2, based on the Peng-Robinson and Non-Random True Liquids equations of state. Process models were built based on the corresponding figures, with additional features such as anti-surge recycling, condensate extractors and flaring systems. Glycol dehydration is simulated with Aspen HYSYS®, using the glycol property package. Power generation units were simulated using the software "Dynamic Networks Analysis" (DNA), which is a component-oriented simulation software developed at the Technical University of Denmark. Off-load characteristics of the compressors and turbines were derived by applying a stage-stacking analysis. The main assumptions are presented as follows:

- Reference state: 5°C and 1.013 bar
- Well-fluid: 1995 m^3.hr^{-1}, Gas-to-oil ratio (Sm^3/Sm^3): 22.7, Water-to-oil ratio (Sm^3/Sm^3): 1.68
- Non-associated natural gas composition: 73.7% CH_4, 6.10% C_2H_6, 6.70% C_3H_8, 2.48% n- C_4H_{10}, 1.41% i-C_4H_{10}, 4.37% N_2, 1.34% CO_2, 0.20% H_2S, 3.70% heavy hydrocarbons
- Ratio flared-fuel gas: 4.7%; lifting-extracted gas: 8.9%; injected water-extracted crude oil: 1.23
- Compression isentropic efficiencies: 53-59-65% (depending on pressure levels and train)
- Pump efficiencies: 61-65-75% (oil pumping train – water injection)
- Pressure losses: 0.15% (coolers and evaporators), 0.30% (mixers), 0.50% (separators)
- Process heating and cooling media: glycol-based thermal oil at 200-225°C and seawater at 5°C

Simulations based on open literature and cases presented in [4, 5, 6] were performed to validate the models of the main process plant and reveal a deviation smaller than 5%. Comparisons between manufacturer data and model predictions were conducted to validate the power generation models.

4 Results

Figure 8 shows the Grassmann diagram of the overall offshore platform, which illustrates that the input and output exergies are largely dominated by the exergy content of crude oil and gas. The main contributors to exergy losses are material streams rejected to the environment without any practical use, such as flared gases or discharged seawater. Exergy associated with lifted gas and injected water is not considered as a loss, since these streams provide the benefit of increasing oil recovery.

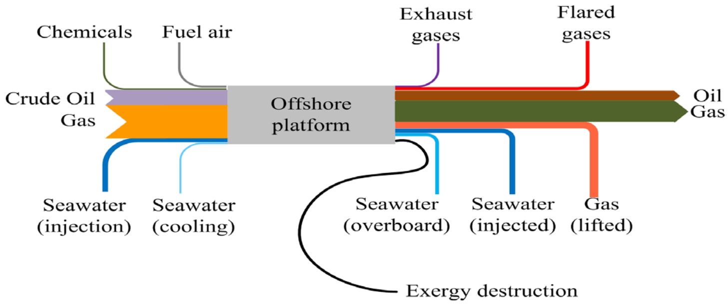

Figure 8: Grassmann diagram of an offshore oil and gas platform

Exergy balance of each process module is given in Table 1 for the baseline case, with exergy flows expressed in MW. No exergetic efficiency could be defined for the production manifolds and separation train, which consist mainly of mixers and throttles to ease the separation process (*).

Table 1: Exergy balances and efficiencies of the different process modules

	Production and Separation	Re-compression	Gas purification	Gas lifting and exportation	Treatment and injection	Oil pumping
$\dot{E}_{d,k}$	8.17	2.61	1.84	8.83	1.21	0.05
y_k^*	36.0%	11.5%	8.1%	38.8%	5.35%	0.25%
$\dot{E}_{f,k}$	*	4.58	6.41	13.1	3.8	0.26
$\dot{E}_{p,k}$	*	1.84	2.66	4.02	2.5	0.21
η_k	*	40.2%	41.5%	30.7%	67%	81%
$\dot{E}_{l,k}$	1.94	0.13	1.91	0.25	0.11	0.01

Total exergy destruction on the offshore oil and gas processes, without including power and heating utilities, totals 22.7 MW. Exergy destruction within the gas lifting and exportation (8.83 MW) and within the production and separation (8.17 MW) steps is much larger than in the other processes. The main reason for the high exergy consumption in the gas lifting and exportation processes is the succession of relatively low efficiency gas compressors, which are used to pressurise gas from 7 to 18 MPa before being either lifted into the petroleum reservoir or exported onshore though subsea pipelines. Nearly equal exergy destruction takes place in the production and separation steps, which is mainly due to the pressure decrease by employing throttling valves.

Gas re-compression and purification are together responsible for about 20% of the total exergy destruction, mainly because of the large inventory of mixers, recycles and pressure losses in the first case, and because of the glycol absorption and desorption columns in the second one. The production and separation step is also associated with high exergy losses, mainly because of the rejection of gas to the atmosphere by ventilation and flaring at the different stages. Similar reasoning applies to the gas purification process, where gas is stripped into the desorber and purged.

Power generation and waste heat recovery are considered separately since they are strongly dissimilar between different platforms and that they are sources of energy for the other processes. Exergy balances and efficiencies are shown in Table 2, with exergy flows given in MW.

Table 2: Exergy balances and efficiencies of the utility systems

	Gas turbine twin-spool systems	Gas turbine one-spool
$\dot{E}_{i,k}$	68.2	17.4
$\dot{E}_{e,k}$	31.8	7.10
$\dot{E}_{d,k}$	36.4	10.3
$\dot{E}_{f,k}$	68.2	17.4
$\dot{E}_{p,k}$	18.3	3.73
$\eta_k(\%)$	26.8	21.4
$\dot{E}_{l,k}$	13.5	3.38

Additionally, the overall exergy destruction rate within the utility systems amounts to 46.7 MW. A more detailed analysis at the component scale reveals that the exergy destruction rate within the combustion chambers of the twin-spool gas turbines accounts for 13.2 MW for each of the two systems, whereas the exergy destruction rate within the one-spool gas turbine accounts for 6.9 MW. The large exergy losses are due to the direct rejection of exhaust gases at high temperature to the surroundings. Comparison with the other processes of the platform shows that the utility system alone destroys twice more exergy than the oil and gas processing plant and is responsible for the largest part of the exergy losses. Total exergy destruction rate within the offshore platform is therefore equal to 69.4 MW, with a share of 67.3% for the utility system and 32.7% for the processing plant. Exergy losses total 22.3 MW, with a respective share of 75.8% and 24.2%.

The exergetic efficiency of the oil and gas processing plant, using the relation proposed by Oliveira [4], is estimated to 39.9%, which is slightly above the value calculated for the case of Voldsund et al. [5, 6] for an offshore platform with complete gas injection. The exergetic efficiency of the power generation system is in the range 21-27%, depending on the gas turbine of consideration.

5 Discussion

Application of exergy analysis, from this study and the researches of Voldsund et al. [5, 6] and Oliveira [4], demonstrates that, for offshore platforms in general, the compression-lifting process ranks as one of the most exergy-destructive steps, while the oil pumping is one of the most exergy-efficient.

However, Oliveira and Van Hombeeck [4] suggested that the crude oil heating operations, within the separation process, are responsible for significant exergy destruction, due to the large temperature difference between the exhaust gases from the gas turbine system and the well-fluid stream. Their conclusions on this part of the offshore system are particularly different from the results of Voldsund et al. [5, 6] and the present findings. These dissimilarities are due to the different properties between the crude oils extracted in the North Sea and in the Brazilian gulf. The feed temperature in the first case is usually around 60-70°C whilst it is about 5-10 °C in the second case.

Comparison with the results of Voldsund et al. suggests that, for North Sea oil and gas platforms, the gas compression process, for lifting and exportation, is the most critical step. Improving this particular process is of strong interest, because it would lead to a reduction of both the energy consumption and the exergy destruction. The fact that these gas compressors are usually run far from their nominal load and need gas recycling to prevent surge is a key issue – alternative process configurations may bring significant improvements.

Considering the present findings, summarised in Table 1 and Table 2, it appears that the utility system of an offshore platform, i.e. the gas turbine and waste heat recovery systems, is responsible for an exergy destruction rate larger by a factor 2 than the overall oil and gas processing system. The operation of the gas turbines in part-load mode and the rejection of high-temperature gases to the environment are problematic: these findings suggest that other configurations and implementation of bottoming cycles such as an Organic Rankine Cycle could present benefits.

6 Conclusion

A generic model of a North Sea oil and gas offshore platform was introduced, modelled and analysed, based on the exergetic analysis method. The largest exergy destruction within the overall system results from the utility system. Exergy destruction taking place within gas lifting and well-fluid extraction is also significant. Recovering more thermal exergy from the exhaust gases, improving the separation plant system and changing process configurations could significantly increase the thermodynamic performance of conventional oil and gas offshore platforms. Conventional exergy analysis does not allow evaluating interactions between the processes of the overall offshore platform. Future work will address this issue by applying an advanced exergetic analysis, which gives a deeper insight of avoidable and unavoidable exergy destruction, and an uncertainty assessment.

Acknowledgements

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